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ABOUT HELIUM

BY

ANDREW STEWART

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INTRODUCTION

From time to time, the Bureau of Mines receives inquiries from the non-technical public on the subject of helium. People ask for information concerning its properties; they want to learn whence it is derived, how it is produced, and to what uses it may be put. In consequence, the following paper has been written to give in simple terms an account of this most remarkable of gases. It has been thought desirable for purposes of analogy to include reference to all the members of the group of elements to which helium belongs, and, incidentally, to embody in the narrative certain other information pertinent to the subject.

Beginning the Story

The story of helium is replete with interest and is unique in the annals of science. The imagination is stirred as one learns how this wonder element, which up to as recently as 15 years ago was obtainable only in very small quantities and at a fabulous cost of the order of $2,500 per cubic foot, is now being produced day by day for about 1 cent per foot and in volumes vast enough to float great airships. One is fascinated as the narrative unfolds concerning the discovery of helium, first as revealed in the gases surrounding the sun, and then as a part of the substances of the earth, and it is learned that this element is actually brought forth by some subtle wizardry of Nature, involving transformation or transmutation of one elemental substance into another.

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Transmutation of Elements--The Alchemists--Molecule and Atom

Transmutation of element into element was once but the chimerical dream of the alchemists, those ancient mystery workers, who, from early Egyptian times down through the gloom enveloping all things intellectual in the Middle Ages, strove in vain to seek out a certain magical agent--the "philosopher's stone," or "elixir"--with which they believed it would be possible, according to a concept of the essential unity of all matter, to resolve substance into substance, more especially, however, baser metals into gold, whereby there would be opened up a source of limitless riches. After them came the investigators of later generations; men who viewed matter as divided into minute masses which they called "molecules", a word from the Latin meaning "little masses." This was no new concept, however. The theory that matter is made up of minute particles had already been advanced by the greatest of Greek physical philosophers, Democritus, and was maintained by him and his followers in the fifth century B. C. But with the passage of time this was forgotten. Molecules represent the limit of physical division, a division not affecting the inherent nature of the substance. A further division is the atom. This represented, initially, the ultimate limit of chemical, or fundamental, mutation, the word "atom" being derived from the Greek and meaning "indivisible."

Up to a comparatively recent day, the succession of investigators following the alchemists laughed to scorn the possibility of transmutation of elements. It was believed that the atom, the soul of the element, was impervious to change. But with the passage of time, bringing enlightenment through research, it has become known that atoms are by no means the limit of material division. Far from it. It has been conclusively shown that atoms are more or less intricate complexes, or systems, of electrical particles (1),[1] and, working on this basis, scientists have been able to cause them to undergo change in structure, giving rise to resolution of one elemental substance into another. Moreover, it has been found that such change occurs even spontaneously in so-called "radioactive" mineral substances, to which reference will be made later.

Thus, strangely, the dream of the ancient alchemist, once considered fantastic, has at last come true. However, the artificial transmutation of element into element has as yet been effected on a scale so small as to be only of scientific interest. It remains for the future to disclose any practical benefit to mankind that may develop from further researches in this field.

The Sun, Birthplace of Helium--Telescope and Spectroscope

From time immemorial the sun, in its majesty, has been an object of man's adoration and wonder. Gradually, however, through the ages, an urge of practical curiosity concerning it began to materialize. The desire to know something of the true nature of the sun took hold on men's minds. But this did not begin to bear real fruit, in the light of scientific investigations, until the illustrious Italian savant, Galileo, in 1609, made his improvement of the

1 Numbers in parentheses, unless otherwise obviously significant, allude to the list of references at the end of this paper.

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telescope, which had been invented in Holland in 1608 (2c). The advent of the telescope, so named by Galileo, was one of the most momentous and interesting events in the scientific development of the world. It furnished the key to unlock the mystery of the heavens and was eagerly grasped and employed by such men as Galileo, Kepler, Harriot, and the distinguished astronomers who have followed after them (3, pp. 6-8).

Among the many subjects for investigation concerning the sun that agitated scientific thought after the advent of the telescope, there were two upon which attention became specially centered, and which, incidentally, led to the discovery of helium. Observed in the telescope were two remarkable solar phenomena: The so-called "sun spots", or dark-appearing areas on the sun's surface, and the fiery prominences or protuberances appearing around the periphery of the sun in the course of an eclipse.

Lockyer--Pioneer in Spectroscopic Solar Observations

A pioneer in interpreting these phenomena was J. Norman Lockyer (later Sir J. Norman Lockyer), the brilliant English astrophysicist. It was he who was the first to employ an instrument, known as the spectroscope, for investigating the physical constitution of the sun, his investigations beginning March 4, 1866 (3, pp. 117, 210 and 436; and 9). Owing primarily to his development of the spectroscope and the art of spectroscopic investigation which he devised and applied to astronomy, the sun spots are now recognized as vast vortices having huge magnetic centers extending over areas of as much as millions of square miles (4, p. 254), while the prominences or protuberances have been revealed as spectacular masses of incandescent gas, mainly hydrogen, forming a part of the gaseous envelope about the sun (3, pp. 125-126 and 390-404). They have been observed to rise from the sun's periphery to a distance of over 500,000 miles (2 d).

The Solar Eclipse of 1868

In 1868 there occurred a total eclipse of the sun. Its shadow included India in its path, and, as it was thought that the eclipse could be seen under particularly advantageous conditions in India, eminent scientists from various parts of Europe made a pilgrimage to that region to have this phenomenon under special observation (3, pp. 119 and 213). As a feature of this activity, the spectroscope was used for the first time to study, under eclipse conditions, the sun's atmosphere, which Lockyer (as suggested by his friend Dr. Sharpey, Secretary of the Royal Society) later called the "chromosphere" (3, pp. 129, 130, and 453). The existence of a continuous stratum or envelope of atmosphere surrounding the sun had been previously suspected by others, but Lockyer was not aware of this. He definitely established it spectroscopically on November 5, 1868 (5). He estimated its average thickness at about 5,000 miles. By the sun's eclipse, when its direct and blinding rays were obscured, this atmosphere was thrown into relief, presenting an ideal, if fleeting, condition for its inspection, together with the magnificiently red- and violet-colored prominences which were observed in all their fiery glory extending far into space. But, as will be

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referred to later, Lockyer, following a method of his own, made his spectroscopic observations in England, in the absence of an eclipse.

The Composition of Light

To digress a moment, daylight, or so-called "white light", is really a composition of various colored lights emitted by the incandescent matter of the sun. This was discovered by Sir Isaac Newton 260 years ago. The sun's substance is now considered to be gaseous, existing, however, under incredibly high conditions of temperature and pressure. Physicists estimate that at its center the sun has a temperature of the order of 29,000,000° C., a pressure of 36,000,000,000 atmospheres, and a density approximately 28 times that of water (4, p. 259).

The Spectrum

When a beam of sunlight is passed through a glass prism, the beam is bent or refracted, from its straight path of travel. But this is by no means all that happens. Since each of the colors composing the light is refracted to a different degree, the prism separates, or disperses, the beam into its components and their colors then become apparent. Therefore, when the refracted beam is caught on a screen it appears as a luminous, colored ribbon or rainbow of light varying in sequence from red, through orange, yellow, green, and blue to violet. This ribbon or band of light is called a "spectrum." This is a Latin word meaning "an appearance", "an image."

The Spectroscope--Fraunhofer Lines

A spectroscope is an instrument, appropriately mounted, having as its essentials a prism, or a number of prisms in series; also, lenses fixed in tubes adjusted respectively for reception and transmission of light from its source to the prism, or prisms in train, and thence, after refraction and dispersion, to the eye, in place of a screen. The light coming to the spectroscope is admitted through a narrow slit-opening in the end of the receiving tube (3, pp. 154-168; 2 b).

Observation of the spectrum of sunlight, the solar spectrum as it is called, through the spectroscope, will show that its bright ribbon of colors is not continuous. It is crossed by innumerable fine dark lines, as first observed by Dr. Wollaston, in 1802. The lines were made visible by his introduction of the narrow slit in the spectroscope to admit the light to the prism, thus establishing the basis of all the modern work which has been done with that instrument. The dark lines were mapped to the number of 576 by Joseph von Fraunhofer (3, pp. 148-152), a celebrated German optician and physicist, in 1814, since when they have been known as "Fraunhofer lines." Many thousand such lines have now been distinguished. This shows that some of the sun's rays have been obstructed on their way to the earth, as will be referred to later.

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Spectra of Solids, Liquids, Gases

Now, when the light from a solid or liquid body, made sufficiently incandescent below its vaporization point (as a piece of white-hot platinum or lime), is passed through a spectroscope, the spectrum formed is a continuous ribbon of succeeding colors of light. It contains no dark lines. But, when a gas or a vapor of a substance under pressure not greatly above atmospheric, or not greatly increased in density, is made incandescent and the light emitted from it is passed through the spectroscope, the resulting refracted light does not give the continuous ribbon; instead, there are visible only some transverse lines of various colors of light appearing at different places along the path of what, in the case of the spectrum of a solid or a liquid, would be the ribbon containing the gradations of the colors of the full spectrum. The spaces intervening between the lines appear black. This is called a bright line spectrum, or, when the lines lie closely crowded together so as to form one or more bands, a band spectrum. A succession of bands with well-marked heads (or specially crowded line aggregates) is called a fluted spectrum.

Spectrum Analysis

In the more complete spectroscopes there is provided either a special adjustment of the observation tube, or a permanently fixed, specially illumined scale, for establishing the exact location of the lines of light. It has been found that each gaseous substance has its different, distinctive lines, which appear at invariably the same respective places in the spectrum. A method for analyzing substances is thereby provided. It is known as spectrum analysis. The science of spectrum analysis was founded by Kirchhoff, in collaboration with Bunsen, in 1859 (2b). By means of it elementary substances can be detected by the spectroscope in amazingly minute traces. For instance (6) a salt of sodium has been recognized by the spectroscope in the almost unbelievably small amount of less than 0.0000003 milligram ($\frac{1}{216{,}000{,}000}$ grain).

A spectroscope with attachment for accommodating photographic plates with which to photograph the spectra, thus making permanent records, is called a spectrograph (7).

The Gas Spectrum

In order to examine a gaseous substance with the spectroscope, so-called "vacuum tubes" made of glass are used. Through each end of these, electrical terminals of platinum and aluminum are sealed. Such tubes are called Geissler, or Plucker, tubes, named for their respective inventors. The vacuum tube is filled with the gas to be analyzed; the gas is then exhausted from the tube, with a pump, until there remains only a very small amount under proportionately reduced pressure. The tube is then sealed by fusing the glass with a blowpipe at the opening where the gas was admitted, and the electrical terminals are connected to a high-tension current, whereupon the rarified gas in the tube becomes highly luminous. Helium gives a brilliant glow ranging from green to canary yellow, with increasing pressure in the tube. The well-known

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brilliant signs for advertising purposes now seen on every street consist of such vacuum tubes, on a more or less pretentious scale, containing various gases. The signs showing the gorgeous crimson light contain neon. Almost any color and tone can be produced by employing certain gases and combinations of these in plain or colored glass tubes (8).

Nature of Fraunhofer Lines

The light from the body of the sun would be seen in the spectroscope without the dark Fraunhofer lines if it flowed to the earth without hindrance, since incandescent gaseous bodies when under great pressure or in very thick volumes, as found in the stars, give continuous spectra just as luminous solids and liquids (2d). However, this light must pass through the atmosphere surrounding the sun and our own atmosphere. The gases of the sun's atmosphere give, of course, bright-line spectra when observed alone, but surrounding the sun they form an impediment to those very rays of light emitted from the main solar body which they themselves give out when in a state of incandescence. The positions in the spectrum which their rays occupy, therefore, appear comparatively dark. Moreover, some gases and vapors in the earth's atmosphere impede certain portions of the sun's light. The theory is that the radiating energy of the rays from the incandescent matter of the sun is absorbed, or used up, in setting in vibration the atoms of the comparatively cooler gases in the solar atmosphere and the gases of our own air through which the rays are projected; therefore, these rays do not get through to the spectroscope, or do so in a greatly weakened state. In consequence, the solar spectrum is called an absorption spectrum.

An analogy is seen in the realm of sound. For instance, if a musical note is struck in the presence of a stretched piano wire, which when set in vibration itself would give forth that note, the struck note will set the wire in vibration. In the same way, when a light encounters a gas which when luminous would give off the same vibration as the light, then the light sets the atoms of the gas in vibration, but its force is thereby weakened or quenched; hence dark or comparatively less luminous lines attributable to it appear in the spectrum instead of light lines. This can be demonstrated by interposing sodium vapors made incandescent in an alcohol flame, between a lime light and the spectroscope. A part of the bright yellow rays given off by the intensely heated lime, corresponding to the vibrations of the sodium spectrum, will be absorbed and appear black, instead of being made more brilliantly luminous by the yellow light from the comparatively cooler and therefore less brilliant sodium vapors in the flame.

There are also many substances, for instance, oxygen, water and iodine vapors, nitrogen peroxide, and solutions of blood and of aniline dyes, which at ordinary temperatures show characteristic selective absorption on passage of light from a white-hot solid through them, and this circumstance provides a further means for spectrum analysis--detection of substances through lines of absorption.

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Stokes, Ångström, Stewart, and Kirchhoff

Light-absorption phenomena were first explained by Prof. (subsequently Sir) George G. Stokes, of Cambridge University, about 1852. This was followed by a further explanation by Ångström. The law which connects radiation and absorption of heat rays was discovered and experimentally proved by Balfour Stewart in 1859. Stewart generalized his conclusions for all rays. In the same year the great German physicist, Kirchhoff, established experimentally the same law for light rays (3, pp. 185 to 195). From what has been said, it will be realized that, to use Lockyer's expression, "the light proceeding from any substance contains, as it were, an autobiography of that substance in a strange language, certainly, but one capable of being translated into the vulgar tongue by passing a light through a prism."

DISCOVERY OF HELIUM

Lockyer's Discovery of Nature of Chromosphere, Sun Prominences.

As has been said, J. Norman Lockyer, back in 1866, conceived the idea of examining the light of the sun spots and of the solar prominences with the spectroscope (3, pp. 117, 210, and 436; and 9). He conceived that if bright lines were revealed by the instrument in the spectrum of the prominences, not only would their gaseous nature be shown, but it would probably be possible to determine of what gases they were composed. However, he found that the spectroscope then available to him did not possess sufficient dispersive power to overcome the exceeding brightness of the body of the sun, which drowned out all subordinate lights.

It should be stated that Lockyer, in pursuing his astronomical work, encountered many serious obstacles, prominent among them being lack of funds, and it was not until October 1868 that this great astrophysicist was in possession of a specially constructed instrument suitable for his purpose. With it attached to his telescope, using this method for solar investigation which he had originated in making his observations in 1866 (3, pp. 210 and 436; 4, p. 233), he conclusively showed on October 20, 1868 (10 and 5), that the prominences did indeed give a bright-line spectrum, and were, therefore, immense volumes of gas, shooting out from a solar envelope of such gas; furthermore, they were composed in part, at least, of hydrogen (3, pp. 125-126; 5).

Lockyer Observes and Fixes Position of Yellow Line

Lockyer also noted a line in the yellow part of the spectrum more refrangible than the two already known D lines referable to sodium, and this line he fixed on November 15, 1868, at a point called D_3 (5). For some time Lockyer and Prof. (later Sir) Edward Frankland (11; and 4, pp. 41 and 238), the distinguished English chemist, who was interested in investigating hydrogen and during a certain period cooperated with Lockyer, putting at his disposition the facilities of his laboratory, thought this line might be due to hydrogen, visible under special solar conditions of temperature and pressure.

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Lockyer Ascribes Yellow Line to Unknown Substance Which he Calls "Helium"

After exhaustive experimentation in an endeavor to produce the line with hydrogen, Lockyer became convinced that it was due to some substance in the sun then unknown on earth. He coined the name "helium" for this substance, in the first instance for laboratory use, deriving the word from "helios", the Greek name for the sun (4, pp. 42 and 274). He was not among those who journeyed to India to observe the eclipse. His spectroscopic observations of the sun were made in England in full daylight. The method he devised made it unnecessary to wait for an eclipse in order to study the prominences.

In his presidential address to the Vesey Club, November 12, 1895, Lockyer gave an account of the discovery of helium, which was printed in the English scientific journal, Nature, of February 6 and 13, 1896. In this address many of the historic facts given herein find mention. Lockyer founded Nature in 1869, and was its editor for 50 years, until 1919, the year before he died.

Observers of the Eclipse in India

Several of the observers of the eclipse in India in 1868, among them the distinguished French astonomer, Janssen, noted a number of bright lines in the spectrum of the solar chromosphere and thus recognized the gaseous nature of the prominences, but they were uncertain as to the exact position of the lines they saw in the spectrum. Captain Herschel, Major Tennant, and M. Rayet each saw varying numbers of lines, one reported as corresponding to D (3, pp. 119-125; 5; and 12).

Janssen's Observations

Janssen made his observations at first during the fleeting moments of the eclipse on August 18, 1868, and then, beginning the next day, for 17 days thereafter he observed the unobscured sun, following a method similar to that which had been proposed by Lockyer in 1866.

Reports of Lockyer and Janssen to French Academy

Janssen reported his findings by telegram to the French Academy of Sciences (12). But he did not observe the D_3 line at that time (3, p. 128), or if he did, it failed to make any special impression upon him. He did not mention it in his telegram, nor in the report that followed it. Lockyer, working in England, on October 20, and observing the same phenomenon concerning the prominences, reported his findings that day to the Royal Society (10). Announcement of his discovery was also made without delay to the French Academy by Warren De la Rue, introducing two letters, one from Balfour Stewart, dated October 21, and one from Lockyer, dated October 23, both addressed to himself. Strangely enough, owing to the distance between India and France and the comparative slowness of travel in those days, the announcement by De la Rue of Lockyer's discovery, and Janssen's report by letter to the Academy (13), were received on the same day only a few minutes apart (14; and 3, pp. 440 and 442).

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Credit for Discovery of Bright Lines in Protuberances

Here was presented a question of proper apportionment of credit for the discovery of the gaseous nature of the prominences. Janssen had actually observed the bright lines in the spectrum of the chromosphere two months prior to Lockyer, but it was Lockyer who, over 2½ years before that, had conceived the idea of investigating the protuberances with the spectroscope and who had originated the method for doing it. He was prevented from making the actual discovery many months earlier than Janssen solely by difficulties beyond his control which kept him from securing a spectroscope of sufficient power for the purpose. However, this excited no feeling of rivalry or jealousy between the two men. On the other hand, it served to cement a sincere and close friendship between them which lasted during the remainder of their lives. The French Academy had a medallion struck in 1868 (4, pp. 40, 41, and 205), commemorating the great discovery. It bears the relief profiles and names of both Janssen and Lockyer, and the inscription: "Analyse des protuberances solaires. 18 aout 1868." (Analysis of the sun's protuberances. August 18, 1868). Janssen died in December 1907. Lockyer died, in his 85th year, on August 16, 1920.

Father Secchi's Observations

The Jesuit priest, Father Angelo Secchi, director of the observatory of the College of Rome, and recognized as one of the world's foremost astronomers, had made spectroscopic observations of the sun at Rome. He verified Lockyer's observation of the new yellow line and was aware that it did not exactly coincide with the double sodium line, being more refrangible and hence nearer the green area of the spectrum (3, p. 461; 5; 15). Father Secchi was born in 1818 and died in 1878. It is interesting to learn that he was not a stranger to the United States, since at one time he was on the faculty of Georgetown University, at Washington, D. C. Lockyer also was personally known here. He was a visitor to the United States in 1878, as an observer of the total eclipse of the sun of that year.

Dr. Hillebrand Almost Discovered Helium in a Mineral

In 1891, Dr. W. F. Hillebrand, then of the U. S. Geological Survey, reported that he had obtained an inert gas by heating uraninite (a mineral containing uranium and thorium) with weak sulphuric acid, in connection with a series of analyses of varieties of this mineral (16). He took this gas to be nitrogen, since it gave chemical reactions attributable to that element, such as evolving nitrous fumes when it was mixed with oxygen and subjected to the action of an electric current discharge, or "sparking," as it is called, and forming ammonium chloride on sparking in the presence of hydrogen and hydrochloric acid. Furthermore, this gas gave the brilliant, fluted nitrogen spectrum. Of course, these reactions proved that nitrogen was present. This won renown for Hillebrand as the first to discover free nitrogen gas in a mineral; or rather, as Hillebrand said, "in the primitive crust of the earth."

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However, Hillebrand found the spectrum of this gas to be somewhat unusual for nitrogen; it contained some strange lines not identifiable with any of the known, mapped ones. Unfortunately, he carried the investigation no further. Failing to do so cost him the distinction of discovering helium on earth. He himself, said in a letter to Professor Ramsay (17, pp. 56-57; 22), who subsequently made the discovery:

> The circumstances and conditions under which my work was done were unfavorable; the chemical investigation had consumed a vast amount of time, and I felt strong scruples about taking more from regular routine work. I was a novice at spectroscopic work of this kind.... It doubtless has appeared incomprehensible to you, in view of the bright argon and other lines noticed by you in the gas from cleveite, that they should have escaped my observation. They did not. Both Dr. Hallock and I observed numerous bright lines on one or two occasions, some of which could be accounted for by known elements--as mercury, or sulphur from sulphuric acid; but there were others that I could not identify with any mapped lines. The well-known variability in the spectra of some substances under varying conditions of degree of evacuation of the tube, led me to ascribe similar causes for these anomalous appearances, and to reject the suggestion made by one of us in a doubtfully serious spirit, that a new element might be in question.

Hillebrand made one observation, the significance of which at that time (prior to the discovery of radioactivity), was not appreciated; namely, that the amount of the supposed nitrogen in uraninite seems generally to bear a relation to the amount of contained uranium, or radioactive substance, in the mineral. As referred to later on in this paper, in general the amount of helium found in a mineral varies with the proportions of radioactive substance

Hillebrand, who passed away a few years ago, was recognized as the master analyst wherever science is known, and methods developed by him are used throughout the world (19).

Lockyer has indicated that if the conditions under which Hillebrand made his spectroscopic examination of the gas he obtained had been different, he possibly would have seen the D_3 line, as Ramsay did, later. For Lockyer brings out the point that under certain electrical and pressure conditions the brilliant, fluted nitrogen spectrum in the yellow could flood that region and thus drown out the D_3 helium line, while under other conditions, for instance those surrounding the observations of Ramsay, the fluted spectrum in the yellow would be absent (4, pp. 278 and 284).

Also, Ramsay has stated (18) that --

> The characteristic spectrum of argon is almost completely masked by the presence of a few parts percent of nitrogen or of hydrogen; and that of helium is similarly affected, although to a less degree.

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> Though no quantitative experiments have been made on the subject, yet I should judge that the presence of from 5 to 10 percent of nitrogen entirely obscures the characteristic yellow line; the other strong lines still remain visible.

Hillebrand, himself, as appears in the above quotation from his letter to Ramsay, was aware that variations can be presented in the spectra of substances, but this apparently served to deter rather than to inspire further investigation by him, although the possibility "that a new element might be in question" was suggested at the time, as stated by him.

Professor William Ramsay and Lord Rayleigh Discover Argon

In the summer of 1894, William Ramsay, professor of chemistry at University College, London, in conjunction with Lord Rayleigh, discovered a new rare gas in the air (17, pp. 15-22). This was the outcome of previous researches conducted by Lord Rayleigh on the vapor density (comparative heaviness) of the principal gases, during which he came upon the epoch-making discovery that "nitrogen" separated from air was of greater density than that prepared from nitrogen compounds. Rayleigh and Ramsay proved that this was due to the presence of a new gas mixed with the nitrogen. On August 13, 1894, this gas was christened "argon", from the Greek word meaning "idle", on account of its inertness, by H. G. Madan (17, p. 22), then Chairman of the Chemical Section of the British Association.

Ramsay's Discovery of Helium in Cleveite

On the alert for other sources of argon, and hearing from the mineralogist, Sir Henry Miers (4, p. 284; 22; and 27, p. 235), of the British Museum, of Hillebrand's experience with uraninite, Ramsay instantly determined to repeat the latter's experiments and to carry them further on the chance of finding argon as a constituent of the gas obtained. With an ardor characteristic of the man, he hastened to secure a sample of the mineral cleveite (one of the uranium-bearing minerals), named for the Norwegian Professor Cleve of Upsala University, Sweden; powdered it; boiled it with weak sulphuric acid; sparked the gas thus obtained with oxygen over soda to remove the oxides of nitrogen thus formed; removed with pyrogallol the excess of oxygen added to the gas; washed the residual gas with boiled water; dried it, and examined it in a vacuum tube with the spectroscope. All this was carried out within 3 days of hearing of Hillebrand's work (21). The lines of argon were found, to be sure, but, to Ramsay's great astonishment, the brilliant yellow line characteristic of helium also appeared. This was in March 1895 (17; 20; 22). At Ramsay's request, Professor (later Sir) William Crookes (23) measured the wave length of the yellow line and confirmed its identity with the line found in the spectrum of the sun. The D_3 line has been found to be really a double line (24).

Thus was helium first recognized as a constituent of the earth's substance. Its discovery by Ramsay was announced in simultaneous communications to the British Royal Society and the French Academy of Sciences on March 26, 1895 (17; 20).

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Other Discoveries of Helium

In the same year, Ramsay discovered helium in a specimen of meteoric iron from Augusta County, Va. (18), and Prof. H. Kayser of the University of Bonn, Germany, discovered helium, with the spectroscope, as a component of the atmosphere, at Bonn. The latter also found helium in the gas emitted from the mineral springs at Wildbad in the Black Forest (25). Helium was separated from the atmosphere by Ramsay and Travers in the summer of 1900 (17, pp. 122-125).

DISCOVERY OF OTHER RARE INERT GASES

With regard to the discovery of other members of the family of rare, inert gases, argon was detected through dual investigations by Lord Rayleigh and Sir William Ramsay, already referred to; krypton, neon, and xenon, in this order, were discovered in the atmosphere by Sir William Ramsay and Dr. M. W. Travers in 1898; and niton (so named by Whytlaw-Gray and Ramsay) (26), or "emanation", now also called "radon", was discovered by Prof. E. Rutherford in thorium compounds in 1900 (28). It is also emitted by radium and actinium. The emanations from thorium and actinium are very short-lived--a matter of seconds; that from radium (detected in 1900 by Dorn after Rutherford's discovery) is far more persistent. It loses one half its activity in about 4 days. The atomic weight of niton was established by Ramsay and Dr. Whytlaw-Gray in 1910 (26).

Rare Gases in the Atmosphere

Argon is contained in the ordinary atmosphere in the proportion of 1 volume in almost 107; neon, about 1 volume in 55,000; helium, about 1 in 185,000; krypton, 1 in 20,000,000, and xenon, 1 in 170,000,000 (29). Niton is contained in exceedingly small amounts in the air.

Prediction of Finding Rare Gases Before Discovery

The research work by which these gases were discovered in the atmosphere and in minerals was of the most brilliant character. The discovery of neon was predicted, with great accuracy, by Ramsay, before it was actually known, and the discovery of other gases was declared certain by him (17, chaps. VII, VIII, and IX). He drew his deductions from data relating to other elements then known, according to the so-called "Periodic Law", formulated independently by Mendeleef, of Russia, and Lothar Meyer, of Germany, which law predicates that the properties of the elements are periodic functions of their atomic weights. Consonant with the Periodic Law (now accepted as a fundamental law of chemistry), all of the chemical elements may be comprehended in a system in which they occupy fixed places and fall into characteristic groups according to, or as a function of, the weights of their respective atoms. Into some of the places for elements in this system which were vacant before the rare gases were known, it was found that they fitted, their properties being largely foretold by analogy even before their discovery.

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Refinement of Technique Sometimes Required by Gas Research-- Niton

So superb was the research technique of Ramsay and Whytlaw-Gray, that in investigating and determining the properties of niton, in 1910 (26; 27, p. 284), they were able to make a series of experiments each of which was performed with the incredibly minute amount of about 1/10 cubic millimeter ($\frac{1}{164{,}000}$ cubic inch) of the gas, weighing about 2/1,000 milligram ($\frac{1}{32{,}400}$ grain), contained in a capillary tube. This was a bubble scarcely large enough to see with the naked eye, much less to manipulate. It was, however, sufficient for these masters. They used in this connection a so-called "microbalance" that was sensitive enough to weigh accurately 1/500,000 milligram ($\frac{1}{32{,}400{,}000}$ grain). This instrument was specially constructed by them, having a beam made of little quartz (silica) rods fused together, all enclosed in a brass case, from which the air could be exhausted. As a counterpoise on the balance a small silica bulb of but 22.2 cubic millimeters (about 1/739 cubic inch) capacity, containing air, was used, and the weighing was effected by regulating the air pressure in the brass case. Silica was chosen as the material for the balance beam, since it is very strong and its expansion by heat is neglible. To make the work still more difficult it had to be done with speed, for, in the space of less than 4 days, one half of the niton became decomposed.

In spite of the infinitesimal amount of niton available to them, Ramsay and Whytlaw-Gray managed to determine some of the physical properties of the gas, but it was necessary in this work to resort to the use of the microscope in making some of the observations (27, p. 290). This digression from the main theme of the narrative has been made to give some idea of the order of refinement which requirements in the field of gas investigation can sometimes demand.

PROPERTIES OF RARE GASES

As already mentioned in this paper, helium is one of a remarkable family of gaseous elements, the other members of which are neon, argon, krypton, xenon, and niton (known also as radon). Their extreme chemical inactivity, or inertness, sets them apart from all other substances. They are completely resistant to ordinary chemical change (30). Respective hydrates of argon, krypton, and xenon are reported to have been prepared, and certain investigators have been active in research work aimed to develop evidence of the possible formation in minute amounts of compounds of helium, argon, krypton, and xenon, with some other elements, under specifically directed and controlled electrical and subatomic stimulus. To date, however, these researches and the results attained are of purely scientific interest (31).

For all practical purposes these gaseous elements are nonreactive. This group, is, therefore, known as the "inert gases", or, by reason of their comparative scarcity, the "rare" or "noble" gases. Their aloofness characterizes

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them as the aristocrats among the chemical elements. They are colorless, odorless, and tasteless, and since they are inert, are nonpoisonous in the ordinary acceptance of the term. They are noninflammable and nonexplosive. Helium, the first to be discovered (as an unknown element in the sun), is the lightest of the series. Next to hydrogen it is the lightest known substance. The weight of a normal liter of helium (a liter at a temperature of 0°C. and a pressure of 760 millimeters of mercury at 0°C.) is 0.1785 gram. The weights of normal liters of air and hydrogen are 1.2929 grams and 0.08988 gram, respectively (32) The specific gravity of helium (air being taken as 1) is therefore $\frac{0.1785}{1.2929}$, or 0.1381, while that of hydrogen is 0.06952. It will therefore be seen that air weighs about 7¼ times as much as helium and 14½ times as much as hydrogen.

Lifting Power of Helium and Hydrogen

Questions have often been asked the Bureau of Mines as to the lifting power of helium. The lifting power of one gas in another depends upon the difference in their densities, or the difference in the weights of respective equal volumes under like conditions of temperature and pressure. For instance, at 60° F. and under the average pressure of air at sea level (14.70 pounds per square inch, which is equivalent to the pressure exerted by a column of mercury 760 millimeters, or 29.92 inches, high) 1,000 cubic feet of air weighs 76.36 pounds and the same volume of helium weighs 10.54 pounds. Under these conditions of temperature and pressure, 1,000 cubic feet of pure helium has a lift in air of 76.36 minus 10.54, or 65.82 pounds; that is, each cubic foot has a lift of 0.06582 pound. One thousand cubic feet of hydrogen, under these same conditions weighs 5.31 pounds, giving a lift in air of 76.36 minus 5.31, or 71.05 pounds--that is, 0.07105 pound for each cubic foot. Helium will, therefore, lift $\frac{65.82}{71.05}$ times 100, or 92.64 percent as much as hydrogen.

The helium, as it comes from the Bureau of Mines production plant at Amarillo, Tex., is better than 98 percent pure. The Government's dirigible, the Macon, holds 6,500,000 cubic feet of such helium, having a gross lifting power of a little over 200 short tons.

Neon is somewhat lighter than air, though slightly more than five times heavier than helium. All of the other members of this series are heavier than air, niton being the heavyweight of the family. It outweighs air about 7½ times.

Why a Steel Cylinder Filled with Helium Does Not Rise in the Air

The question has several times been asked the Bureau why a standard-sized steel cylinder filled with compressed helium gas does not rise in the air, since helium is so wonderfully light. The idea in the minds of the interrogators seems to have been that the more of this light gas that can be forced into the cylinder, the more it will lift.

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There are two main conditions that affect the density of a gas, or to state it more simply, the heaviness or the lightness of a gas. These are temperature and pressure. If a gas is heated, the pressure remaining constant, it expands; it becomes thinner and the same amount of the gas is thereby made to occupy a greater volume; it is therefore lighter per unit volume. If, on the other hand, the gas is cooled, under constant pressure, it contracts and there is consequently more of it occupying the same given volume; it becomes denser and consequently, heavier. Furthermore, if the pressure on a gas is increased, the temperature remaining constant, it is squeezed together, becomes denser and consequently heavier per unit of volume. If the pressure is decreased, the temperature remaining constant, the gas expands, becomes thinner and, consequently, a given volume of it is lighter. It will therefore be readily seen that the more helium there is compressed into a cylinder, the heavier the gas will become. Helium gas is transported and stored in standard-sized steel cylinders which are of about a foot and a half actual space capacity. The helium is compressed under a pressure that exerts a force of about 1,800 pounds on each square inch of the inside of the cylinder wall. When the helium in the cylinder, under these conditions, is released to ordinary atmospheric conditions of pressure and temperature, it will occupy a volume of about 178 cubic feet. So 178 cubic feet of helium has been compressed into the space of $1\frac{1}{2}$ cubic feet. In consequence of this it has been made so dense that it has now become about 17 times as heavy as the surrounding air. It will therefore not exert any lifting power, but, on the contrary, adds about 2 pounds to the 130 pounds, more or less, that the cylinder itself weighs.

Gradation of Properties in Rare Gases

Beginning with helium and running through neon, argon, krypton, xeon, and niton, in this order, there is to be observed a general gradation of certain physical properties of the remarkable family of rare gases to which helium belongs. This is noted with regard, for instance, to density, molecular weights (the weights of the respective free-existing, infinitesimally small physical particles of which they are composed), refractive index and dispersion (or the way light is changed on passing through them), and boiling and melting points (33; 31). In some properties, such as heat conduction, solubility in water, viscosity (resistance offered by a substance to the relative motion of its particles), and compressibility, the progression is broken to some extent for no reason now definitely known. All of these gases are monatomic; that is, their molecules contain but 1 atom. Therefore, their respective molecular weights are the same as their atomic weights. In tthe case of helium this weight is 4 (oxygen gas being taken as a standard, or 16). Helium is the most difficult of all gases to liquefy and solidify.

The Absolute Scale of Temperature

The theoretical point of absolute cold lies at -273.1°C. (-459.58°F.). This point is called the absolute zero. Temperatures reckoned from this zero are called absolute temperatures (Abs.), or Kelvin temperatures (K.) in honor of the distinguished English physicist, Lord Kelvin. At the absolute zero, molecular motion ceases entirely and there is no heat, since heat is but a

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manifestation of molecular energy. In the absolute system of temperatures, either the centigrade or the Fahrenheit interval of degree may be used. In practically all scientific work, however, it is standard practice to determine temperature by the centigrade scale. In this scale zero temperature, 0°C., is the temperature of melting ice or freezing water, and 100°C. is the temperatur of boiling water when the pressure, in each case, is 1 atmosphere (760 millimeters of mercury). In the Fahrenheit scale, 32°F. is the freezing temperatur of water and 212°F. that of boiling water, at 1 atmosphere pressure, with an interval of 180° between, compared with 100° on the centigrade scale, or a ratio of 9 to 5

Gas Measurements--Laws of Boyle and Charles

The following elemental discussion of how gas measurements may be calculated according to the so-called "Gas Laws", is given for the information of any reader who may be specially interested.

The two laws evolved, respectively, in the seventeenth century by the great Irish scientist, Robert Boyle, who was the son of the Earl of Cork, and in the eighteenth century by J. A. C. Charles, the eminent French mathematician and physicist, are often used to compute changes of gas volume with changes of pressure and temperature. Charles, by the way, was the first to employ hydrogen in balloons. This was in 1783 (2a).

Boyle's Law

Boyle's law states that, if the temperature of a given mass of gas is kept constant, the volume varies inversely as the absolute pressure (the pressure starting with the true zero of pressure); or, the product of the volume times the absolute pressure remains constant. To illustrate the application of this law, consider a quantity of gas that occupies a volume of 100 cubic feet when its temperature is 0° C. and its absolute pressure is 1 atmosphere (14.7 pounds per square inch). If the absolute pressure is raised to 2 atmospheres (29.4 pounds per square inch, or twice the original pressure), and the temperature remains at 0° C., the volume will be reduced to one half of the original volume, or 50 cubic feet. If the absolute pressure is raised to 100 atmospheres (1,470 pounds per square inch) the volume will be reduced to $\frac{1}{100}$ the original volume, or 1 cubic foot.

In this connection, it should be stated that gages, by which pressures are ordinarily measured, do not register absolute pressure. Their zero point represents 1 atmosphere pressure. They therefore show the difference between the pressure within the container to which they are connected and the pressure of the atmosphere surrounding the gage. That is, if a pressure gage surrounded by air under atmospheric pressure at sea level (14.7 pounds per square inch) is connected to a vessel that contains gas under 2 atmospheres absolute (29.4 pounds per square inch) the gage will show only 1 atmosphere (14.7 pounds per square inch). If it is connected to a vessel that contains gas under 100 atmospheres absolute (1,470 pounds per square inch) it will show only 99 atmospheres (1,470 minus 14.7, or 1,455.3 pounds per square inch). Therefore, in order to obtain the absolute pressure of gas within a vessel it is necessary to add the pressure of the atmosphere to the pressure reading shown by a gage connected to the vessel.

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Charles' Law

Charles' law states that if the pressure of a given mass of gas remains constant, the volume varies as the absolute temperature (the temperature scale whose zero is 273.1° C. below 0° C.); or, the volume divided by the absolute temperature remains constant. To illustrate the application of Charles' law, again consider the quantity of gas that occupies a volume of 100 cubic feet when its temperature is 0° C. (273.1°K.) and its pressure is 1 atmosphere. If the absolute temperature is raised to 273.1° C. (546.2° K.) and the pressure is not changed, the volume will be twice the original volume, or 200 cubic feet. The absolute temperature has been doubled; therefore, the volume has been doubled.

Laws of Boyle and Charles Combined

If the laws of Boyle and Charles are combined, we find that the volume of a given mass of gas, times its absolute pressure, divided by its absolute temperature, is a constant quantity. Expressed mathematically, using V to represent the volume, P the absolute pressure, T the absolute temperature, and C the constant quantity,

$$\frac{PV}{T} = C.$$

To illustrate the combined laws, suppose we take a quantity of gas having a volume of 100 cubic feet at 0° C. (273.1°K.) and 1 atmosphere of pressure. Assume that the absolute pressure is raised to 100 atmospheres and the absolute temperature is raised to 100°C. (373.1°K.) and it is desired to know the new volume of the gas under these conditions. Let V' represent the unknown new volume and P' and T' represent the new pressure and temperature, respectively.

According to the foregoing expression, since

$$\frac{P'V'}{T'} = C, \text{ and } \frac{PV}{T} = C,$$

then

$$\frac{P'V'}{T'} = \frac{PV}{T}.$$

To find the new volume which has become, under the new conditions, the unknown quantity, V', the known quantities may be substituted in the equation, giving

$$\frac{100 \times V'}{373.1} = \frac{1 \times 100}{273.1}$$

from which

$$V' = 1.3662 \text{ cubic feet.}$$

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Strictly speaking, the laws of Boyle and Charles apply only to what may be conceived as the hypothetical "perfect" or "ideal" gas. Since the days of Boyle and Charles, it has been found that real gases do not follow these laws exactly; they may be more compressible or less compressible than the hypothetical "perfect gas", depending upon their composition and the initial and final temperatures and pressures involved in the change. However, for computation of changes of volume of gases, when they are well removed from temperatures and pressures under which they liquefy, these laws may be used without introducing large errors, and it is beyond the scope of this paper to develop the mathematical formulas to take into account departures from them.

Compressibility of Helium

Within ordinary ranges of temperature and pressure, helium is slightly less compressible than the "perfect" gas would be. For instance, it has been found experimentally that 100 cubic feet of helium at 0°C. and 1 atmosphere pressure would be reduced to 1.4167 cubic feet if its temperature were increased to 100°C. and its pressure were raised to 100 atmospheres. Since the volume for the ideal gas would be 1.3662 cubic feet, the volume of the helium would therefore be 3.7 percent greater. To that extent it is less compressible than the ideal gas under the specified conditions.

Further Properties of Rare Gases

Although helium does not conduct heat quite as well as hydrogen, which is the best heat conductor of all gases, it is about six times as good a conductor as air (34, vol. V., p. 213). It conducts electricity better than any other true gas, except neon. Collie and Ramsay (35) reported that a spark discharge 250 to 300 millimeters long could be obtained in helium under conditions as to electric potential and pressure of gas that produced spark discharges in other gases with mean results as follows: Oxygen, 23.0 millimeters; air, 33.0 millimeters; hydrogen, 39.0 millimeters; and argon, 45.5 millimeters.

Liquefaction of Helium

It is necessary to reach the extremely low temperature of about 5.2°C. above the absolute zero (5.2°K. = -267.9°C. = -450.2°F.) in order to liquefy helium (34, vol. III, p. 248). Helium was first liquefied by the Dutch scientist, Prof. Kamerlingh Onnes, at the University of Leiden, on July 10, 1908 (36), since when its liquefaction has been accomplished by Professor McLennan and associates (37) of the University of Toronto; by Walter Meissner, March 7, 1925, at the Physikalisch-Technische Reichsanstalt, Berlin (38); by Professor W. H. Keesom of Leiden (39); by Dickinson, Brickwedde, Cook and Scott (41) on April 3, 1931, at the U. S. Bureau of Standards, Department of Commerce, Washington, D. C.; by Goez and Focke at the California Institute of Technology (72); at Oxford University, England; at Breslau; and possibly elsewhere.

Liquid helium is colorless, mobile, and transparent. Next to liquid hydrogen, it is the lightest liquid known. Its density at its boiling point is 0.126, water being taken as a standard, or 1, while the density of liquid

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hydrogen at its boiling point is 0.071 (34, vol. I, p. 102; vol. III, p. 20). The maximum density of liquid helium is at 2.3°K. (34, vol. I, p. 102). It boils under atmospheric pressure at about 4.2°K. (34, vol. III, p. 203), has a critical temperature (the temperature above which it cannot exist as a liquid at any pressure) of 5.2°K., and a critical pressure, or pressure at the critical temperature, of 2.26 atmospheres (34, vol. III, p. 248).

Onnes liquefied helium, prepared from the mineral monazite, by passing the gas through an apparatus in which it was cooled, first to the temperature of liquid air (about -192°C., or -312°F.) and then to 15°K. (about -432.6°F.), by surrounding it with liquid hydrogen boiling under reduced pressure and thereupon expanding the helium through a nozzle or valve. By this means, 60 cubic centimeters (about 2 fluid ounces) of liquid helium was obtained in 3 hours from 300 liters (about 10½ cubic feet) of the gas.

Solidification of Helium

Professor Keesom, another Dutch scientist, was the first to solidify helium, which he did at Leiden, June 25, 1926 (39). Onnes had tried to solidify the gas by lowering the temperature alone (39) and attained the extremely low pressure of less than 1/50 millimeter of mercury, at which the temperature was estimated to be 0.82°K., but the helium remained liquid.

It is interesting to record that Professor Giaugue and D. P. McDougall, on April 9, 1933, while carrying out experiments on demagnetization of gadolinium sulphate, starting with a temperature of 1.5°K., produced with liquid helium, reached a temperature of 0.25°K., just a quarter of a degree above the point of absolute absence of heat (40).

Professor Keesom succeeded Professor Onnes at the University of Leiden, on the untimely retirement and subsequent death of Onnes. Keesom used the cooling method of Onnes. In the final stage a surrounding medium of liquid helium itself, boiling under reduced pressure, was employed. However, he also applied pressure, which was the further requirement necessary for success. On July 1, 1926, continuing his experiments, he solidified helium at various temperatures from 4.21°K. down to 1.19°K., according to the pressure employed, from 140.5 atmospheres or 2,065 pounds per square inch to 25.3 atmospheres or 372 pounds. A homogenous, transparent, crystalline solid was obtained which was so tough that it could be hammered.

Simon, Ruhemann, and Edwards succeeded in solidifying helium at 20°K., and about 1,800 atmospheres pressure. This is remarkable, since the solidification temperature under this condition is about four times as great as the gas-liquid critical temperature (42).

Thus helium, the most difficult of all gases to liquefy and to solidify was finally conquered by the skill and perseverance of the scientist.

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Laboratory Method for Separation of Helium from Other Gases

Helium can be separated from other gases, except hydrogen, by a process of adsorption. On passing the gas mixture through specially prepared, or activated, cocoanut charcoal at the temperature of liquid air, exercising careful control and, if necessary, repeating the process, the accompanying gases can be completely adsorbed and the helium, spectroscopically pure, can be pumped off. This method is used by the Bureau of Mines in determining the helium content of natural gas. No authentic instance of natural gas containing hydrogen has come to the Bureau's notice in its helium-bearing gas investigations.

SOURCES OF HELIUM

Radioactive Substances

After helium was discovered in minerals, it was found that this element is a product of the spontaneous disintegration of radioactive substances, as shown by Ramsay and Soddy (43). These strange everchanging bodies, three series of which--uranium-radium, thorium, and actinium--are known, are found in minerals and rocks (44; 62, p. 11). Their atoms give off, or emit, three types of radiant energy, called alpha, beta, and gamma rays. The alpha ray, or particle, emitted at an enormous rate of speed, of the order of thousands of miles per second, is a helium atom carrying two positive charges of electricity. In other words, the alpha ray is an evolved, electrically-charged helium atom. This loses its charges spontaneously and becomes finally ordinary helium.

Recent research experiments have shown that helium may be produced artificially by bombardment of certain substances (lithium, boron, some hydrocarbon compounds, etc.) with high-velocity electric particles--protons and alpha rays (45).

Radioactive minerals are very widely distributed throughout the earth's crust, but in comparatively small aggregations; consequently, helium also is found in many places in the earth's outer substance (46) but generally, excepting in certain natural gases to be mentioned later, in neglibible amounts.

Mineral Springs and Volcanic Gases

Helium is present in minute quantities in natural waters, and has been found in the gases given off by certain mineral springs, and in volcanic and fumarole gases. In the boracic acid fumaroles, or openings in the earth giving forth steam, fumes, and gases at Larderello, in Tuscany, Italy, helium is evolved in small content, of the order of 0.10 to 0.15 percent (47). In gases given off by hot springs in Iceland, helium was found only to the extent of 0.0006 to 0.0104 percent (48).

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Origin of Atmospheric Helium

The presence of helium in air, already referred to, has been considered by some to originate in its evolution during the disintegrating changes in the radioactive minerals of the earth. Others account for it on the theory of primordial existence. At the earth's surface, the air contains about 1 volume of helium in 185,000 volumes. It has been asserted that the atmosphere at the height of 100 miles is principally hydrogen and helium, and at 500 miles in composed entirely of these two gases.

Minerals, First Source of Helium

Naturally, minerals were the first source of recovery of helium. The amounts obtainable were, however, limited, being sufficient only for scientific investigational work, while the cost of production was prohibitive for other than such purposes. It is estimated that, before helium was produced from natural gas, the cost of obtaining it from minerals amounted to as high as $2,500 per cubic foot. Probably not more than 100 cubic feet had been produced in the world, most of which precious hoard was owned by Professor Onnes of Leiden, Holland. Contrasted with this, as will be referred to later, in a single month, January 1932, more than a million and a half cubic feet were isolated in the production activities of the United States Bureau of Mines helium plant, near Amarillo, Tex., from natural gas of the Cliffside structure, of the Amarillo gas field, at a net operating cost for that month of about one half cent a cubic foot.

Radioactive Ores

Among the minerals, it is radioactive ores of the groups containing uranium and thorium in which, as a general rule, helium is to be looked for in appreciable amounts. The initially active substances in these minerals are the uranium and thorium. These original elements through spontaneous decomposition produce three long series of other radioactive substances, which themselves undergo further transmutations, one into the other. The final product arrived at, in each series, is lead. This lead appears to be the ultimate member of the series, as it exhibits no further radioactivity. At certain disintegration stages, in this evolution of new elements, atoms of helium are given off (44).

Helium Contained in Minerals

The amount of helium in the mineral depends in general on its amount of contained uranium or thorium, the age of the mineral, and its capacity for retaining or occluding this element. Strangely enough, however, there are some minerals rich in helium that contain little or none of these radioactive substances: the beryls, for instance. However, just recently (49) a new instance of radioactivity, the explosion of the beryllium atom, has been discovered. Measurements by Rutherford and Boltwood indicated that a gram of radium (disintegration product or uranium) will produce helium at a rate of

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164 cubic millimeters per year. Cleveite, pitchblende, carnotite, fergusonite, samarskite, thorianite, and monazite may be mentioned as radioactive mineral sources of helium. The last-named, being found in greater quantities, offers the best raw material of this character. Monazite sand, a mineral composed of phosphates of cerium and other rare earth metals and containing 5 to 10 percent thoria (thorium oxide), is found in comparatively small amounts, of no present commercial importance, in the United States (50). The largest supplies are located in southern Brazil, and in the province of Travancore, on the southernmost tip of India. Monazite is exported from India in rather large tonnage for its content of thoria, from which incandescent gas mantles are made.

Recovery from Minerals

The helium may be obtained from such minerals by simply heating the finely ground substance to suitable temperatures; also by heating with dilute sulphuric acid, in case the mineral is soluble in that reagent; otherwise by fusion with acid potassium sulphate. The helium given off must then be purified to remove contaminating gases, such as nitrogen, argon, and in some cases hydrogen, carbon dioxide, carbon monoxide, and hydrocarbons. About a quarter of the contained helium may be liberated simply by pulverizing the mineral to a sufficient degree of fineness and pumping off the gas, as the helium is held merely occluded, as such, in minute cavities or pores in the mineral, and is not in actual combination. Helium has been recovered from cleveite at a rate of 7.2 cubic centimeters per gram; from thorianite, 8.9 cubic centimeters; from monazite sand, 2.41 cubic centimeters.

Separation of helium from monazite sand has been carried out in the chemical research laboratory at Teddington, Middlesex, England (51). A recovery of between 26 and 27 cubic feet of 96.5 percent helium per short ton of sand was effected by heating the material to high temperatures and purifying the gases liberated. By purifying with metallic magnesium and calcium, heated to red heat, a purity of at least 99.5 percent was attained. The sand was imported from Travancore, India, and contained helium of the order of 1 cubic centimeter per gram.

Helium in Gases of Mineral Springs and Mines

Helium has likewise been collected from gases given off from mineral springs, but only in limited amounts. Although the percentage of helium content of some of these gases, in Europe, runs comparatively high--over 10 percent in at least one instance--the total amounts of the gases themselves do not permit of consideration for any but limited helium recovery. It has been estimated that the Cesar Spring at Neris (Allier), France, one of the largest of such sources of helium, evolves about 1,200 cubic feet of the gas per year. The gases from these springs consist in a few instances chiefly of carbon dioxide; the great majority are rich in nitrogen, resembling in this respect some of the natural helium-bearing gases of the United States (52; 62, pp. 49-51). A number of examinations by the Bureau of Mines of gases in the United States from springs, both hot and cold, and of geysers have

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failed to reveal more than traces of helium. The Bureau has also examined oil shale, coal, and gases from coal and metal mines without finding any appreciable amounts of helium. Helium has been found in small percentages in gases of French and Belgian coal mines (62).

Discovery of Helium in Natural Gas from Dexter, Kans., by Cady and McFarland

In 1903 a rather shallow gas well which, however, gave a strong flow of gas was drilled at Dexter, Cowley County, Kans. In consequence there was great rejoicing in the little village. The advent of this gas was hailed as the harbinger of great prosperity. Visions of Dexter expanded to the proportions of an important center of natural gas activity and wealth swam before the eye. But the joy was premature and short-lived; the goose that was to lay the golden egg died before the egg appeared, for, to the consternation of all concerned, the gas was found to be almost noninflammable and practically worthless as fuel. It would not burn unless played into a fire kept going by ordinary combustibles. A sample of the gas was therefore sent to the University of Kansas for examination, in order to discover the cause of its astonishing, perverse behavior. There, on analysis, it was found (53, 54) that the gas contained very little combustible matter, not over 15 percent, but was over 80 percent nitrogen and other inerts. In view of the work of Ramsay and Rayleigh in connection with the discovery of argon, this "nitrogen" was subjected to some sparking with oxygen, but the residuum was reserved for further analysis when time should permit. Later, in 1905, Professor H. P. Cady and Dr. McFarland subjected this residuum to carefully conducted further examination and found that it contained helium (55) and that the gas from the Dexter well had a helium content of 1.84 percent. Thus was helium for the first time discovered as a constituent of natural hydrocarbon gas.

Helium Discovered in Other Natural Gases

Following the discovery of helium in the gas from Dexter, Cady and McFarland, pursuing their investigations further, succeeded in finding helium in a large number of gases from Kansas and a few from other States (55, 56). They also found argon and neon in some of these gases.

A gas from Augusta, Kans., that contained 1.97 percent of helium was analyzed by C. W. Seibel (57) for neon, argon, krypton, and xenon. He found that all of these gases were present, and he showed that their relative proportions in the gas were different from those in which they are contained in atmospheric air.

Noncombustible Natural Gases Do Not Necessarily Contain Helium

From time to time the Bureau of Mines receives communications reporting the finding of gas issuing from shallow water wells, openings and fissures in the ground, and even from the surface, with the statement that the gas will not burn, and that it must, therefore, be helium. The correspondents are led to this conclusion because they have heard that helium is noninflammable.

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However, helium has never yet been found naturally evolved in such a state of purity that it would extinguish flame, and the content of helium in even the richest of helium-bearing natural gases is so small as to have little effect on the inflammability or explosibility of the gas.

Although certain natural gases will not burn, it is the presence of unusually large amounts of constituents other than helium, such as nitrogen, as in the Dexter gas, or carbon dioxide, that prevents combustion. Nitrogen is present in the general run of ordinary natural gases to the extent of anywhere from 1 percent up to 30 or 40 percent, but it has been found in some cases as high as 99.66 percent. Carbon dioxide is ordinarily present in amounts of less than 1 percent, but some gases issuing from wells have been found to be almost pure carbon dioxide. As both nitrogen and carbon dioxide are noncombustible, the effect of their presence on the burning power of natural gases in amounts as above set out, will be obvious. Therefore, the fact that a naturally occurring gas will not burn is not necessarily an indication that it contains helium. In fact, the natural gas of the Petrolia gas field, Clay County, Tex., which was for some years processed for helium production by the Government, had satisfactory burning qualities, and the gas near Amarillo which is being used to supply the present nearby Government plant has excellent heating value. After passing through the helium-removal process the gas is used for fuel both in the plant and in the city of Amarillo.

Various Constituents in Helium-Bearing Natural Gas

Most helium-bearing natural gases contain some nitrogen, but, on the other hand, many of the gases that have a large nitrogen content do not contain enough helium to be detectable by ordinary methods of gas analysis. Oxygen is rarely present, and then only in small amounts. Such gases do not contain carbon monoxide or hydrogen, except possibly in rare instances, but some of them contain poisonous hydrogen sulphide, at times in concentrations fatal to animal life. A content of this lethal gas as high as 20 percent has been found.

Determining Heating Value of a Fuel Gas

The ordinary practical standard of measurement used to determine the heating value of fuels is the British thermal unit (B.t.u.), which is the amount of heat necessary to raise the temperature of 1 pound of water 1°F. The heating power of fuel gases is usually figured in terms of the number of B.t.u.'s produced by the combustion of 1 cubic foot of the gas under some selected standard condition of pressure and temperature. A number of such standards are in use. In natural gases it is the hydrocarbon content that furnishes the heat of combustion.

Helium-Bearing Natural Gases

As has been stated, helium in sufficient quantity for large-scale production and use is derived only from certain natural gases which contain the helium as such. Helium production from natural gas means simply the separation, or isolation, of the helium from the other gaseous constituents. The

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rich helium-bearing natural gases are found in regularly drilled gas wells, extending to so-called "sands", or porous rocklike subterranean formations in which the gas is held captive. Neither natural gas nor petroleum is found in the earth in large, free, unbroken volumes, but is contained in the interstices of "sands" under pressure, called "rock pressure." Some of these helium-bearing gas sands are located comparatively near the surface, as, for instance, the original discovery well at Dexter of which the depth is only 325 feet; but generally they lie much deeper, as far down as 3,600 feet at least, or something more than three fifths mile, as on the Cliffside structure of the Amarillo gas field.

It has been found that natural gases containing helium are widely distributed over the United States, but so far only a few localities have been discovered in which the volume of the gases themselves and their helium content are sufficiently large for economically practicable helium production. These favorable conditions prevail in the region of northwestern Texas. However, in addition to helium content and volume of gas, economic production of helium depends on many engineering and other factors, such as efficiency and costs of process, cost of the gas (initial purchase cost, leases, royalties, etc.), marketing or disposal of residue gas after processing, topographical and geographical situation of the gas, available water and fuel supply for the production plant, transportation facilities and cost, distance to market, consumption demands, and market price. In some parts of Kansas, gases running as high as 3.5 percent in helium content have been found, but investigations carried out by the Bureau of Mines, with the cooperation of the United States Geological Survey, have so far indicated that the resources of the helium-bearing gases themselves, in Kansas are less favorable than those in Texas. As far as is known, the same may be said of Colorado and Utah where gas running as high as 7 or 8 percent in helium has been discovered.

Bureau of Mines Helium-Bearing-Gas Survey

The Bureau of Mines has maintained for several years—in fact, ever since the entrance of the United States into the World War--a comprehensive survey of the natural gases and gas-producing areas of the United States, for helium for Government purposes. During this period several thousand samples of gas from wells located in the majority of the States have been examined. This investigation is still in active progress and forms a vitally important part of the Bureau's helium work, for it is obvious that the operation of the Government's lighter-than-air ships depends, in first instance, upon the maintenance of an adequate and continuing supply of helium-bearing gas. Incident to this survey the Bureau found that a gas in a dome on lands of the public domain near Woodside, Utah, contained about 1.3 percent of helium. This gas has no fuel value, as it has over 90 percent inert carbon dioxide and nitrogen, and the location of the dome, for several reasons of economic and engineering importance, is not particularly favorable for low-cost helium production; however, an area of about 12,000 acres, covering the dome, and insuring the gas against wastage from any gas operations which might be conducted in that locality, was set aside, as authorized by Congress, as a reserve resource for the Government's use in case of war-time emergency.

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World's Helium-Bearing Gas Resources

The greatest known resources of natural gas in the world are in North America. These include all sorts of natural gas. So far, the United States is the only country in the world in which helium-bearing gases in amounts sufficient for helium production for aeronautical purposes have been found.

Canada

Helium occurs in the natural gases of several provinces of Canada, notably in Alberta and Ontario, but the amount of the helium-bearing gases is small. According to Elworthy (58), the richest of these gases, produced in Peel County, Ontario, has a helium content up to 0.82 percent, and Rosewarn and Offord (59) report gas from one well in the same province having 1.03 + percent of helium. The generally prevailing low helium content of Canadian gas and the consequent high cost that would be involved in processing it, do not permit of production on a scale large enough and at costs low enough for practicable use in aeronautics. Elworthy estimates that around 5,000,000 cubic feet of helium per year might be recoverable, but this assumes that most of the helium is to be extracted from gases containing as little as from 0.2 to 0.37 percent, with an 80 percent recovery, and that questions of cost are not to be considered. Experience in the United States has demonstrated that, in the present status of the art, production of helium from gas with less than 1 percent of helium is not attractive from an economic standpoint.

Europe and the Orient

Helium has been found in natural gases in some countries in Europe and the Orient, but only in extremely small amounts. Such countries are Australia and New Zealand, Japan, Transylvania (largest European natural gas-producing territory), and Germany. In the last-named country, helium has been just recently reported in Neuengamme, Heide, Oberg, Volkenroda, Leopoldshall, Ascheberg, and Ablen, but in no case was the occurrence as great as 0.2 percent

PRODUCTION OF HELIUM

Historic Evolution

The production of helium on a large scale was born of the necessity of war, projecting the use of helium in military and naval aeronautics. Employment of lighter-than-air craft, except for specialized scouting activities, particularly in connection with strategic operations of the fleet at sea, was an exceedingly hazardous undertaking in the World War, due to the extreme inflammability of the hydrogen gas with which the craft were inflated. The hydrogen was easily ignited by incendiary bullets, and during the hostilities many of the German Zeppelins that were sent over England for bombing purposes were thus brought down in masses of flame. On the other hand, it has been reported that the German fleet never put to sea without one or more Zeppelin scouts flying far overhead, able, from the lofty vantage point of their far-flung field of observation, to sight enemy ships and give timely notice of their positions and movements.

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Efforts of Ramsay, Threlfall, McLennan, and Others

As already described, the combined properties of inertness and buoyance of helium gas had been established by Ramsay and others long before the World War. These properties were recognized as ideal for a balloon gas, and scientists had considered the possibility of the use of helium in airships. The question was where to obtain the helium. Ramsay had examined mine gases in England without avail. He also knew of helium content in Canadian natural gas. But the first to give any practical impetus to solving the problem of acquiring helium on a large scale was Sir Richard Threlfall, in England, in 1915 (58; 60). Threlfall (who passed away on July 10, 1932) was aware of the helium content of natural gases in America. He was chairman of the Fuel Research Board, a member of the Advisory Council of Scientific and Industrial Research, and of other kindred organizations in England.

Search for Helium in Canada

Through representations that Threlfall made to the British Admiralty, a sum of money was appropriated and made available to Prof. J. C. McLennan, of the University of Toronto, to institute a search for helium within the British Empire (60) and, in the event that adequate supplies were found, to carry on experiments for the development of a process for its recovery. As a result, early in 1916, samples of gas from most of the producing Canadian gas fields were examined (58; 60), and it appeared, as an outcome of this work, that establishment of experimental helium production plants in Canada might be feasible at only two locations: namely, Hamilton, Province of Ontario, and Calgary, in Alberta. At no other place in the British Empire were helium resources found of any considerable importance.

Experimental Plant in Canada

In 1918, a small experimental plant was constructed and tried out near Hamilton, the work being participated in by Profs. John Satterly, E. F. Burton, and H. F. Dawes, and by John Patterson, Lang, and others, but the gas proved inadequate in amount and the plant was later moved to Calgary, to process gas from the Bow Island field. Finally, from December 1919 to April 1920 a series of trial runs was made. It has been reported that, in all, only about 60,000 cubic feet of 60 to 90 percent helium was produced before the plant was finally shut down.

Inception of Helium Production in the United States

In April 1917, shortly after the United States had entered the war, the American Chemical Society held its annual meeting at Kansas City, Mo., and on this occasion the paper by C. W. Seibel, already referred to (57), concerning the recovery of rare gases from natural gas, was presented. The reading of this paper gave rise to a discussion during which the late Dr. R. B. Moore, then of the Bureau of Mines, brought up the possibility of separating helium from natural gas in amounts practicable for lighter-than-air military service.

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It was also in April 1917 that the Director of the Bureau of Mines placed G. A. Burrell (later Colonel Burrell) in charge of the Bureau's war-gas work. The Bureau of Mines had initiated this work, chiefly on gas masks, smoke screens and toxic gases, in cooperation with the Army and the Navy. Burrell, who had been engaged in gas investigations for the Bureau of Mines for several years before the war, had analyzed samples of natural gas from many localities and had found helium in them. He had thought of helium as a possible filler for balloons and dirigibles.

Burrell thought of the possibilities of the gases of the Petrolia field, in Texas, in regard to helium yield on account of their large nitrogen content. He had samples sent to Dr. Cady for analysis. These samples were found to contain about 1 percent of the element. Thereupon, Burrell took up the question of utilizing this gas for helium recovery with the Director, with Dr. F. G. Cottrell, and others in the Bureau of Mines.

Experimental Production by the Bureau of Mines with Army and Navy Funds

The proposition to provide means for investigating the feasibility of large-scale helium separation from natural gas for military and naval aeronautics was initiated by Burrell, Dr. Moore, and other officials of the Bureau of Mines with the hearty approval of the Director. The matter was taken up by Burrell with the Army in a letter on May 12, 1917, to Major C. de F. Chandler of the Signal Corps. These activities resulted, eventually, in an allotment of funds from Army and Navy appropriations to undertake an experimental helium production program, the Bureau of Mines being authorized to conduct the technical work (61).

Pioneering Gas Investigations

From examinations of natural gas obtained from various localities in the United States, as well as geologic investigations by the United States Geological Survey (62) and the Bureau of Mines following the extensive pioneering work by Professor Cady and Dr. McFarland already mentioned (55 and 56), it was concluded that the Petrolia gas field, in Clay County, Tex., on the north-central border of that State, was the best source of helium-bearing gas at that time available, having the combined prime essential qualifications of adequate helium content and volume of gas.

Development of Production Process

The difficulties in the way of extracting one gas from another, when the desired gas is present in the comparatively insignificant proportion of less than 1 part in 100 parts, were at once apparent. This would mean undertaking the processing, in billions of cubic feet, of a raw material having over 99 percent undesired matter. However, since it was known that the natural-gas constituents other than helium could be liquefied at temperatures which would leave the helium, most difficult of all gases to liquefy, in a state of gas,

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the employment of a method of separation based upon this circumstance was obvious. The principal constituents of the natural gas, methane, ethane, and nitrogen, could be separated from the helium in this way. Under the pressure of 1 atmosphere, ethane becomes liquid at -88.6°C. (-127.5°F.) (34, vol. III, p. 217); methane at -161.4°C. (-258.5°F.) (34, vol. III, p. 216), and nitrogen at -195.8°C. (-320.5°F.) (34, vol. I, p. 102). At the pressures usually obtaining in production cycles the liquefaction points of these gases are somewhat higher. Helium will not liquefy above a temperature of -267.9°C. (-450.2°F.) (34, vol. III, p. 248).

Cooperating Agencies--First Helium Produced

Since the process contemplated for helium production was analogous to cycles already in use for production of oxygen from the air by liquefaction, whereby the oxygen (about one fifth part of the air) is separated from the nitrogen (about four fifths part) by fractional distillation, several firms interested in that line of work were invited to cooperate with the Government. Three of these responded, and during 1918 three plants for experimental try-out of their respective oxygen-production processes, appropriately modified, were erected under cognizance of the Bureau of Mines (61). The firms cooperating were the Linde Air Products Co., the Air Reduction Co., and the Jefferies-Norton Corporation. One of these try-out plants was placed at Petrolia, Clay County, Tex., near the Petrolia gas field, and the other two were at Fort Worth, Tex. About 200,000 cubic feet of helium, all told, were produced by them in their experimental runs. About 147,000 cubic feet of this helium, compressed in steel cylinders, was on the dock at New Orleans, ready for shipment to France for use in observation balloons, when the Armistice closing the war was signed. In the operation of the experimental plants many technical data essential to economic, large-scale helium production were developed, and invaluable practical experience was gained.

Experimental Plants Point Way for Large-Scale Production, Then Pass out of Existence

Having served their pioneering purpose, the experimental plants passed out of existence after the close of the war, and a large production plant was then constructed in which was installed the Linde Air Products Co.'s modified production cycle.

Production Plant at Fort Worth

This was the U. S. Helium Production Plant, located just north of the city limits of Fort Worth, Tex. (63). It was constructed under cognizance of the Navy, with the Linde Air Products Co. cooperating, during the period May 1919 to April 1921. The separation equipment was operated under contract by the Linde Co., subject to the direction of the Navy, until July 1, 1925, when, pursuant to Congressional enactment, responsibility for the Government's entire helium conservation and production project, including the plant and

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pipe line, passed under the jurisdiction of the Bureau of Mines (64). The plant was placed in an inoperative status, January 10, 1929, by reason of the approaching exhaustion of the Petrolia gas field, its source of supply.

In this plant was produced about 46,000,000 cubic feet of helium, figured on a 100 percent basis. The process represented no easy task. It involved many complicated scientific problems, for the working out of which but scanty technical data existed. For every cubic foot of helium recovered, over 120 cubic feet of gas had to be processed. The gas came to the plant from the Petrolia field, about 100 miles distant, through a Government-owned 10-inch pipe line.

Petrolia Gas Field

At the time of the erection of the production plant at Fort Worth, it was known that the Petrolia gas field would not last for many years, since the field was 10 years old when the Government's helium project started. However, it was then the only known source of helium-bearing gas sufficient in quantity and of high enough helium content to warrant consideration for large-scale helium production.

Nocona and Amarillo Fields

The foreshadowed exhaustion of the Petrolia gas field made it necessary for the Bureau of Mines to locate a new supply of helium-bearing gas. Two sources of such gas were discovered, one in Montague County, Tex., known as the Nocona gas field, and the other in Potter County, Tex., known as the Cliffside structure, in the Amarillo gas field. Although the Cliffside structure was the best of the known sources for large-scale, continuous, and prolonged production of high-grade, helium-bearing natural gas, the Nocona gas field was under serious consideration for a time, because it could be connected to the plant at Fort Worth. However, rapid oil development and consequent wastage of the gas by oil operators destroyed the Nocona field's desirability, and a decision was made to build a new plant near Amarillo.

The Government-Controlled Cliffside Structure, Source of Supply for Amarillo Project

The gas of the Cliffside structure is approximately twice as rich in helium as that from the Petrolia field. Governmental control has been so far secured as to assure that this gas can be conserved. This structure is located

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a few miles to the north and west of the city of Amarillo, a modern progressive community of about 45,000 inhabitants, situated at about the center of the Texas Panhandle. Work toward the acquirement of gas reserves, anticipating erection of a plant at Amarillo, was started by the Bureau of Mines in 1926, when it was apparent that the supply of gas for the Fort Worth plant was rapidly failing. The Cliffside structure was then known to produce gas averaging about 1.75 percent helium content. In 1927, an operating contract for gas, with option (to purchase gas rights), covering 20,000 acres of land on the Cliffside structure was entered into by the Government. This was followed by exercising the option, and effecting other contracts and purchases. These together give the Government control of gas in about 50,000 acres of land. The reserve of gas in the structure and the Government's control over it assure the Army and Navy adequate supplies of helium for many years.

Drilling for gas to supply the Amarillo plant was started in February 1928, and upon completion of this work the Bureau of Mines was in possession of four helium-bearing gas wells, with a total open-flow capacity of about 30,000,000 cubic feet of gas per day, located on the Cliffside structure.

The Amarillo Helium Production Plant

In July 1928, construction of the pipe line from the Cliffside structure to the plant site was started and a contract was awarded for erection of the plant buildings, ground being broken early in August. The first separation unit of the plant was placed in regular production in April 1929, after helium in preliminary, or tune-up, operations had been recovered as early as in January. Since that time the efficiency of the plant was steadily increased and there has been a marked reduction in operating costs. A second separation unit of the plant was completed in May 1930. Both of these units were designed by Bureau of Mines technical men and were erected under their supervision. The separation apparatus of the second unit was built in the well-equipped machine shop maintained as an essential plant facility.

Description of Plant

This plant is known as the United States Bureau of Mines Amarillo Helium Plant (65). It is at Soncy, a point on the Rock Island Railway about 7 miles west of Amarillo, occupying a site of about 18½ acres, inclosed in a high, strong, wire-mesh fence. Highway No. 66 passes east-west, along the front of the plant, and the railroad parallels it outside the rear line of the reservation. The plant consists of an aggregation of eight major buildings of permanent construction, together with their appurtenances, including roadways; water-cooling pond; water wells and tower; gas holders; water, steam, gas, electric, and waste lines. A spur, or switch, leads into the plant enclosure from the main track of the railroad. Economic, engineering, and sanitary conditions for helium production activities at Soncy are very favorable. The altitude of the place is nearly 4,000 feet above sea level and climatic conditions are good. The water supply is adequate and good in quality, and the B.t.u. value of the gas is finely adapted to power production. The plant is connected with the wells on the Cliffside structure by a Government-owned, 6-inch, welded steel

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pipe line, about 12 miles long, together with appropriate gathering lines, which operate at a pressure of from 600 to 700 pounds per square inch. The residue or processed gas is conducted from the plant to the City of Amarillo for industrial use, through a pipe line of 10-inch diameter.

Capacity of Amarillo Plant--Production and Costs

The plant at Soncy is capable, with its present two-unit equipment, of producing regularly and easily well over 24,000,000 cubic feet of helium per year. It has, however, never been run at its maximum capacity, because helium at that rate has not yet been demanded by the Government's military services. From the beginning of operations in April 1929 to May 1, 1933, the plant produced about 51,000,000 cubic feet of helium, figured on a 100 per-cent basis, at an average net cost for operation and maintenance of $9.60 per thousand cubic feet. Net cost, here, means expenditures in operating and maintaining the plant and gas field, less return from sale of residue gas. This cost, and those referred to in following paragraphs, are based on the actual helium contained in the airship gas supplied from the plant to the Army and Navy.

The unit cost of output depends to a large degree upon the rate at which the plant is operated. Items of cost which make up a considerable part of the total operating expense remain practically the same whether the output is large or small. Therefore, when the production is increased, there is only a slight rise in total operating expense, and consequently, a marked decrease in cost per thousand cubic feet of helium produced. Through experience gained in operation and economies and efficiencies introduced as time went on, the net average production cost for the fiscal year ending June 30, 1932, was brought down to $7.10 per thousand cubic feet.

As an illustration of what is possible with large output and under favorable conditions, special reference may be made to the month of January 1932. The costs for that month were the lowest thus far attained. Using only one of the two separation units, the plant produced 1,652,200 cubic feet of helium with expenditures of $12,544.48 ($7.59 per thousand cubic feet of helium produced) for operation and maintenance of the plant and gas field. There was a return of $4,401.50 from residue natural gas sold during the month, giving a net operating cost of $8,142.98, or $4.93 per thousand cubic feet of helium. This is less than one fifth of the lowest monthly net operating cost attained in the old production plant at Fort Worth.

Purity of Helium Produced

In addition to producing helium at greatly lowered costs, the Amarillo plant has improved the quality of the helium as it is produced and supplied to the Army and Navy. Prior to the operation of this plant, the average purity of the helium received by the military services was 95 percent, or less. Now, the Amarillo plant is regularly producing helium of better than 98 percent purity. Since an increase of even 1 percent in purity of the helium adds about 2 tons to the lift of a ship the size of the Macon, the increased purity of the Amarillo product is of great advantage in operation of the Nation's lighter-than-air craft.

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In experimental work, looking to still further improvement in the quality of the plant's output, the cryogenic laboratory of the Bureau has succeeded in bringing the purity of a considerable quantity of helium up to 99.96 percent.

Helium versus Hydrogen as Balloon Gas

In the final analysis it costs less, under present conditions, to operate Government airships with noninflammable helium than it would to operate them with inflammable hydrogen. The first cost of hydrogen, if produced for airship operation, might be less than the present cost of helium; however, in the operation of lighter-than-air ships, there is a constant diffusion of air into the gas cells and of buoyant gas from the cells out into the surrounding atmosphere. This gradually lowers the lifting power of the gas and makes it necessary either to reinflate the ship with entirely new gas, or to purify the gas charge and add new gas to make up the lost volume. This has to be done several times a year.

Contaminated hydrogen must all be thrown away, for there is no known process for safe and economic purification of hydrogen in such large volumes as are required in aeronautics. On the other hand, helium may be drawn from the airship and purified at a cost of only 50 cents to $1.50 per thousand cubic feet, in plants that have been designed and built by the Bureau of Mines for the Army and Navy. The purified helium is then replaced in the ship and new, make-up helium added to restore the ship to its proper buoyancy.

Purification of Air-contaminated Helium

In purifying the helium, the contaminating air is liquefied by a process similar to that used in producing helium from natural gas. The impure helium is pumped under high pressure through a coil or purifier to which is attached a drain pot to catch and remove the liquefied impurities (air), the whole being surrounded by liquid air obtained in the operation of a separate cycle. This process cannot be applied to purify hydrogen, since the oxygen of the contaminating air might form with the hydrogen an exceedingly explosive mixture, which would probably blow up the plant. The helium required for replacement of gas losses in an airship over the course of a year's operation is only about 1 to 1½ times the volume of the ship, compared to 8 to 10 times the volume in the case of hydrogen.

Helium Production Process at Amarillo

Most gases under pressure, when permitted to expand, cool themselves down. They also cool themselves when, on expanding, they are made to perform external work, for instance in the cylinder of an expansion engine. Both of these circumstances are made use of in the production of helium by liquefaction of the constituents of helium-bearing natural gas other than the helium contained therein.

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Preliminary Removal of CO_2, and Other Contaminants From the Gas

The gas from which the helium is extracted at Amarillo contains carbon dioxide up to about 0.7 percent. This must be eliminated before the liquefaction process can be carried out, otherwise it would solidify at the low temperatures attained in the plant and plug the apparatus. It is removed, as a preliminary step, by scrubbing the gas with a 7 percent solution of caustic soda in an extended system of steel tubing under the pressure of 600 pounds at which the gas comes to the plant from the field. The water vapor accumulated in the scrubbing process, and some higher hydrocarbons of the gasoline series, are eliminated in the first part of a system of heat interchangers (or exchangers) through which the gas, still at 600 pounds pressure, now passes.

Production of Crude Helium

Through these interchangers the raw gas coming into the plant runs countercurrent with and is precooled by cold residual gas leaving the system, after having the helium removed. The hydrocarbon constituents of the gas and most of the nitrogen are liquefied and separated in this step. They are finally volatilized, pass out of the plant as residue gas, and are conducted through a pipe line to Amarillo for use as fuel. The gas phase remaining, consisting of about equal parts of helium and nitrogen, is collected at lowered pressure as "crude helium."

Crude Helium Stepped up to Better than 98 Percent Purity

This crude helium is next compressed and passes through a purifying process in which it is conducted through a second series of heat interchangers and finally enters a container (or pot) surrounded by liquid nitrogen, liquefied by the aid of expander engines in an auxiliary system. In this container, at the low temperature of about 312° below 0° F., and the high pressure of 2,500 pounds, the nitrogen of the crude helium is almost entirely liquefied and drawn off, while the helium, now at better than 98 percent purity, is reduced to ordinary temperature, through interchangers, and conducted to tank cars, or small steel cylinders, for transportation; or it is placed in a high-pressure storage system at the plant. A small part of the nitrogen is recovered in the purification process and used as a make-up for losses in the auxiliary nitrogen liquefaction cycle.

Within the Cycle

At the minimum temperature of about 312° below 0° F., reached in the plant, atmospheric air is a liquid, carbon dioxide and mercury are solids, lead becomes tough and elastic, and copper takes on a strength approaching that of steel. Rubber becomes as brittle as glass. Placing an icicle in the ultra-cold liquefied gases in this plant would be like thrusting a hot poker into tap water. The temperatures in the processing apparatus are measured by so-called "thermocouples"; delicate instruments recording the temperatures in

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terms of electric currents which are transposed into thermometric degrees. Each cubic foot of natural gas comes to the plant at ordinary temperature and under a pressure of about 600 pounds per square inch; it passes through the plant at express-train speed, is dropped in temperature to about 250° below 0°F., and is again raised to ordinary temperature, all in the sensationally small space of less than a minute of time. It leaves the plant at about 75 pounds pressure.

Transportation of Helium--Tank Cars and Cylinders

The tank cars in which helium is transported from the plant to the Army and Navy flying fields each consist of three or more large, heavy-walled, seamless steel cylinders mounted on railroad trucks. The Navy has at present several of these cars. The Army has two. They are specially designed and constructed for helium transport and accommodate helium at a pressure of from 2,000 to 2,250 pounds per square inch, which, when expanded to ordinary atmospheric conditions, occupies a volume of from 200,000 to 215,000 cubic feet. By use of these cars a material saving is effected in transporting helium, on the score of reduced freight rates, saving of time and labor in handling, and a minimum of escape of gas on filling and discharging, as well as reduced leakage through valves.

The small cylinders, which are usually shipped in box cars, are of the standard hydrogen or oxygen type, each having an actual space capacity of about 1½ cubic feet and are shipped under a pressure of 1,800 pounds per square inch, holding an amount of gas which, when expanded to ordinary atmospheric conditions, occupies about 178 cubic feet. They are fitted with double-seated valves instead of the single-seated variety usually employed in handling other gases. Since it requires between eleven and twelve hundred of these cylinders, occupying two freight cars, to transport the same amount of helium as one tank car, the economies in the use of the tank cars will be obvious.

Helium Storage at Amarillo Plant

At the Amarillo plant, a permanent high-pressure storage equipment has been installed, consisting of about 24,000 small helium cylinders of the standard description mentioned. Their valves have been removed and the cylinders have been connected with a manifolded system of tubing. This storage has a capacity of about 3,500,000 cubic feet of helium when filled to a pressure of about 1,500 pounds per square inch.

Helium and Other Rare Gases Separated from Air

Comparatively small amounts of helium, as well as commercial volumes of argon and neon, are recovered as by-products in the industry of producing oxygen by liquefaction and separation of air. Helium and neon, which liquefy at temperatures far below those required to liquefy nitrogen, argon, and oxygen, may be drawn off as a gaseous mixture when the other constitutents of the air have been liquefied. The helium and neon may be separated by differential adsorption when

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passed through activated charcoal at very low temperature. They may also be separated by freezing out the neon with liquid hydrogen. Argon, which has a liquefaction temperature lying between those of nitrogen and oxygen may be liquefied along with those two elements and separated from them by fractional distillation of the liquid.

CRYOGENIC, OR LOW-TEMPERATURE, RESEARCH

Inception of Cryogenic Laboratory

From what has been said, it is obvious that the production of helium from natural helium-bearing gas involves many scientific and engineering problems concerning the properties and manipulation of gases and liquids at low temperatures and high pressures. When helium production was initiated, the data then existing in this field were scanty, and it early became apparent, as the Government helium project developed, that a laboratory devoted to research along these lines was absolutely essential to success. The Bureau of Mines cryogenic research laboratory was therefore established.

Laboratory Opened by Madame Curie

The laboratory was formally opened in Washington in May 1921 by Madame Curie, the eminent French scientist, codiscoverer of radium, who was in the United States on a visit at that time. This laboratory was ultimately removed to the plant at Amarillo, Tex., and installed in a building constructed expressly to meet its requirements.

Experimental research has been carried on continuously in this unit by a specially trained corps of technical men, and data have been evolved which have been of utmost value to the Government's helium production and purification projects, especially in developing designs for the Amarillo plant. Not only were scientific data evolved in the laboratory, but their practical application was tried out in experimental, laboratory-scale plants, designed for improvement of helium production processes, preliminary to the building of full-scale plants. In this way great economies of time and money were effected.

Work of Cryogenic Laboratory

As now conducted at Amarillo, the work of the cryogenic laboratory includes, in addition to strictly cryogenic research, the supervision of all control analyses pertaining to the production plant and its allied facilities, and performance of analyses relating to the Bureau's continuing gas field investigations. This latter activity comprehends examinations of numerous samples of natural gas, from locations throughout the country, for content of helium and other constituents.

An indispensable adjunct of the cryogenic laboratory is an equipment consisting of compressors and liquefiers with their appurtenances, for producing liquid air, essential in carrying on the low-temperature researches and for

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the analyses of natural gas for helium and other constituents. In this apparatus liquid air can be produced in amounts up to about 15 quarts an hour.

In analyzing natural gas for helium content, as done in the cryogenic laboratory, the gas is passed through a system, included in which are glass bulbs filled with a certain variety of specially prepared (activated) charcoal. These bulbs are immersed in Dewar flasks filled with liquid air, at the temperature of which (about -312°F.) all of the constituents, save the helium, are adsorbed and the helium, thus isolated, is collected and its volume measured (62, pp. 41 and 42).

Helium Purification Plants Designed and Built by Bureau of Mines for Army and Navy

Data for the design of plants for purification of helium after use in airships were developed as coming within the scope of the activities of the cryogenic laboratory. A plant was built by the Bureau of Mines for the Naval Air Station, at Lakehurst, N. J. Two plants built by the Bureau for the Air Corps of the Army, one a mobile and the other a stationary unit, are located at the Army Air Station, Scott Field, Belleville, Ill., near St. Louis, Mo. The helium for inflation of the great Navy dirigibles has been purified in the Lakehurst plant.

USES FOR HELIUM

While the outstanding practical, large-scale employment for helium is in floating balloons and airships, other uses for this unique element are being found. It is probable that the number of uses will increase in proportion as more is learned of the properties and adatability of the gas and greater quantities of low-cost helium may become available.

Use in Deep-Sea Diving and Caisson Work

In connection with the use of caissons, also with reference to shaft sinking and tunneling, where operations are conducted under pressures increased above atmospheric for the purpose of excluding water from the working place, the Bureau of Mines as far back as 1922 investigated the subject of controlled oxygen content and greater diffusibility of certain gases (66) in artificial respiratory atmospheres. It was discovered that helium might be used to great advantage in the make-up of such atmospheres, not only in facilitating caisson work, but also in the operations of deep-sea divers, who are obliged to carry on their activities under increased pressure.

Effect of Air Breathed Under Increased Pressure

Air is, roughly, one fifth oxygen and four fifths nitrogen. It contains, however, a number of other constituents, minor in amount, such as water vapor, carbon dioxide, hydrocarbons, nitrous and nitric acids, ammonia, ozone, hydrogen peroxide, and rare gases (67). The blood and other tissues of the body

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normally contain some air, but if they are subjected to air pressure above atmospheric, as, for instance, when a diver descends into the sea or when a man is at work in a caisson, increased amounts of air are taken up. If the pressure is great, so much air, and particularly the nitrogen portion of the air, is absorbed that on return of caisson workers or divers to a normal environment, unless extreme care is observed and much time allowed for the change of condition (the so-called "decompression" period), the absorbed nitrogen will collect as bubbles, and these, emitted from the blood and tissues, will cause a pathological condition known as the "bends", which in some instances may be severe enough to cause death.

Effect of Artificial Helium-Oxygen Atmospheres

An exhaustive series of experiments by the United States Bureau of Mines, in cooperation with the United States Public Health Service and the Navy Department (68), has demonstrated that through the use of artificial breathing atmospheres in which helium is substituted for nitrogen and the proportion of oxygen is somewhat reduced, divers and caisoon workers can work for more extended periods and under higher pressures with greatly increased safety and comfort, and may be returned to normal pressure conditions in a fraction of the time required when compressed air is the atmosphere breathed while at work. The pressure-illness and hazard to life from this source of danger are thereby practically eliminated. This is because helium at pressures not far removed from the ordinary is not only inert but is extremely insoluble, being, next to neon, the least soluble of gases. Also its molecule is much smaller than that of nitrogen, and therefore its diffusion is more rapid.

Various Uses Suggested in the Arts and in Medicine

Uses for helium may be found in metallurgical processes, by reason of its inertness and of its comparative insolubility in metals, either molten or otherwise. On account of its inertness, hot metals may be worked in an atmosphere of helium without suffering corrosion or gas occlusions. The following suggestions which have been made for other practical applications for helium might be mentioned: As a preservative for food; in connection with refrigeration processes, by reason of its high conducting power for heat; for cooling electric motors, and for fireproofing high-tension switch boxes, on account of its inertness and high heat conductivity. Furthermore, the use of helium may be indicated in certain medical and surgical applications, according to the results of experimental researches already carried out.

Scientific Uses

There are several ways in which helium has been of service in the research laboratory as an aid to the scientist in his never-ending quest for facts and reasons underlying Nature's phenomena. It finds application in thermometry, for recording extremely low temperatures. It has also found use in spectroscopy as a primary light standard, and to demonstrate properties of electric waves (69). Just recently, it has been proposed to refer all atomic weights of the elements to helium, the helium atom being taken as 4, in place of the usual standards, hydrogen as 1, or oxygen as 16 (70).

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Liquid Helium and Electrical Superconductivity

With helium as the instrumentality, the remarkable property of electrical supraconductivity or superconductivity was discovered. It was Kamerlingh Onnes who made the discovery while experimenting with liquid helium in 1911. Liquid helium, it will be remembered, boils under atmospheric pressure at 4.20° K. Onnes found that mercury cooled by liquid helium suddenly lost all resistance to the passage of electric current at 4.19°K, becoming a superconductor (71). Certain other metals, alloys and metallic compounds, have also been found to become superconductors, or perfect conductors, at various respective temperatures peculiar to each (called "transition" temperatures), in the general region of the temperature of boiling helium, or below. For instance, for titanium and gallium this temperature is at the ultra-low point of 1.1° K. As long as these temperatures are maintained electric currents started in the superconductors persist apparently in undiminished intensity.

Singularly enough, some metals classed under ordinary conditions as poor conductors, such as mercury, lead, and tin, possess this astonishing property of superconductivity, while some excellent conductors, such as pure silver, copper, and gold have so far failed to show it. Then there is the case of copper sulphide, which although composed of a nonsuperconductor, combined with an element which is actually one of the best nonconductors, or electrical insulators, becomes, strangely enough, superconducting at 1.6°K.

No satisfactory theory has yet been advanced in explanation of superconductivity. Judging from facts already developed, it has been surmised that, placed under proper conditions, not as yet however fully recognized, all metals will probably be found superconducting. How far-reaching the discovery of superconductivity will prove to be cannot now be foreseen (72).

Uses in General

In conclusion, it may be said that wherever a perfectly inert gas, or a buoyant gas, or one having high conducting power for heat and electricity, or low solubility, is desired, helium may find application.

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